1 Introduction

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1.1 History and Purpose of Quarantine and Phytosanitation Requirements

Introduction

Heat has had a variety of uses since primitive times, such as in cooking and food preservation, but its use was limited as a pest control method for stored products until the modern era. Heat can be generated by various ways: chemical oxidation, combustion, electrical resistance and electromagnetic exposure, and heat treatments have been devised that take advantage of each.

The manner in which heat is produced affects both products and their pests, and the success of a given treatment depends on its ability to control insects without causing product damage. This chapter will briefly review the history and development of product treatments in general and heat treatments in particular that meet pest phytosanitation and quarantine security requirements. Terms used in the regulatory processes will be defined, and a short review of the current status of heat treatments will be presented.

Treatments

Postharvest treatments are a recent development. For most of human history, insect pests in stored products have been tolerated. However, two events led to the development of postharvest methods to eliminate insects. The first relates to the distribution of pest insects, which historically was limited by their biology and geophysical forces. With increased travel by humans – particularly wide-ranging exploration and commerce – insects can now be transported into new areas. If the insect has potential to do damage, even though it is a minor pest in its native range, measures that prevent its introduction and establishment are needed. This concern has resulted in a series of procedures and regulations pertaining to quarantine insects.

The second event that led to the development of postharvest methods to eliminate insects involved the rapid evolution of agricultural technology to store surplus commodities until future consumption or transport to distant markets for greater economic gain (see Table 1.1, which illustrates the huge global market for two particular commodities, fruit and nuts). To prevent damage during storage by various insects – particularly beetles and moths, phytosanitation procedures were developed to reduce and control the populations of these pests. Because of the complexities of modern commerce, the distinction between quarantine and phytosanitation is often unclear.

Quarantine Regulations

Quarantine statutes involve the treatment or shipment of an agricultural commodity from one location to another. They can be imposed by various bodies: (i) local governmental jurisdiction, such as the Washington State (USA) quarantine against intrastate movement of apples from areas where fruits have been infested with the apple maggot, *Rhagoletis pomonella* (Walsh) (Diptera:

Table 1.1. World export of fruit and nut products.

	Four-year average (2000–2003)	
Commodity	Quantity (metric tonnes)	Value (US$1,000)
Fruits		
Cherries	155,769	388,011
Dates	494,863	260,179
Figs (fresh and dried)	88,270	141,338
Grapefruit and Pomelos	1,037,373	475,102
Grapes	2,806,023	2,701,020
Lemons and limes	1,737,864	796,061
Mangoes	714,655	437,758
Olives	36,813	34,761
Oranges	4,783,691	2,024,224
Papayas	209,718	132,112
Peaches and Nectarines	1,222,043	1,007,580
Pineapples	1,294,431	589,146
Plums	434,231	351,183
Prunes (dried plums)	160,846	267,899
Raisins	632,459	607,248
Strawberries	492,654	789,275
Tangerines	2,564,985	1,559,091
Nuts (shelled and in-shell)		
Almonds	393,268	1,099,125
Hazelnuts	224,843	557,993
Pistachios	211,212	697,965
Walnuts	186,885	460,667

Tephritidae); (ii) within national boundaries, such as the quarantine against movement of cherries from the US Pacific Northwest states to California (CDFA, 1998) because of possible infestation by cherry fruit fly, *Rhagoletis cingulata* (Loew) (Diptera: Tephritidae); or (iii) between nations, such as the quarantine of possible host materials of the codling moth, *Cydia pomonella* (L.) (Lepidoptera: Tortricidae), in exports to Japan (MAFF–Japan, 1950).

To facilitate the implementation of such quarantines, groups of nations within a region have formed organizations that provide similar regulations against a common potential pest. Laws involving the importation of commodities that may contain the Caribbean fruit fly, *Anastrepha suspense* (Loew) (Diptera: Tephritidae), imposed by nations in the European and Mediterranean Plant Protection Organization (EPPO), are good examples.

Other international regulatory organizations include the Caribbean Plant Protection Commission, Inter-African Phytosanitary Council and the North American Plant Protection Organization. Individual countries have their own plant protection agencies, such as the Australian Quarantine Inspection Service, Ministry of Agriculture, Forestry and Fisheries (Japan) and Animal and Plant Health Inspection Service (USA). Regulation within a country often falls on a local or state government body, such as the US California Department of Food and Agriculture and Washington State Department of Agriculture.

All of the above entities may write their own regulations to meet immediate concerns and generate lists of quarantine pests. For example, the EPPO has a list for quarantine pests not present (A1 pests) and another for quarantine pests present but not widely distributed and officially under control (A2 pests). The state of California has a similar rating system, with 'A' pests requiring that infested commodities be rejected or treated, and 'Q' pests temporarily requiring the same action as A pests until a permanent rating can be determined. To assure exclusion of the quarantine pest, these lists include all potential hosts.

Enforcement of quarantine regulations relies primarily on international trade agreements and standards that may include the use of specific treatments on select commodities to assure quarantine security. Hence, international commerce in commodities potentially containing quarantine pests is strictly regulated.

Phytosanitation

Phytosanitation generally does not involve regulation as extensive as that applied to quarantine. Rather, economic considerations direct its application. It benefits the producer to promote commodities free of pests, both to restrain internal costs and to promote an attractive product. The burden of phytosanitation usually falls on the fruit or produce packer or marketer, and treatments may be applied repeatedly.

Probit-9 and Quarantine Security

The standard of quarantine security for many importing countries is probit-9, or 99.996832% mortality of the pest population (Robertson *et al.*, 1994b). In practical terms, probit-9 means that only 32 individuals can survive out of 1 million treated pests. Originally suggested by Baker (1939), the use of probit-9 was directed at those not familiar with sophisticated experimentation and data analysis. Baker used moisture-saturated hot air to control the Mediterranean fruit fly, *Ceratitis capitata* (Wiedemann) (Diptera: Tephritidae), on Hawaiian kamani nuts shipped to the American mainland, and intended that the criteria used to calculate probit-9 mortality be successful adult emergence from a single batch of insects.

Probit-9 security levels are normally applied to quarantine treatments of commodities that have a high and frequently unknown level of pest infestation. In practice, this condition is often ignored. For example, cherries imported to Japan from the Pacific Northwest of the USA must be treated with quarantine procedures that have demonstrated probit-9 efficacy on the last codling moth instar, even though intense postharvest inspections demonstrate its rare occurrence. Between 1978 and 1996, one potential codling moth larva was identified from out of 4.9×10^8 individually inspected fruits from the Pacific Northwest region of the USA (Wearing *et al.*, 2001).

In developing a new quarantine procedure, it is very difficult to produce the probit-9 level by treating 1 million insects at one time. Instead, a probit model is developed based on a dose-response curve from much smaller populations, and then projected out to the probit-9 level to determine the quarantine treatment. A statistical test may be included to determine whether the original data fit a probit distribution. Confirmatory tests are then performed, during which the proposed quarantine treatment is tested against a large number of pest insects.

Some countries require a specific number of test insects to be treated during confirmatory studies: 30,000 test insects with no survivors are commonly used. Although this approach is flawed by several severe statistical problems, described in detail elsewhere (Landolt *et al.*, 1984; Chew, 1994; Robertson *et al.*, 1994a, b), many regulatory bodies continue to base their quarantine programs on probit-9 security. A more thorough discussion of the mathematical approaches for determining efficacy is given in Chapter 5, this volume.

1.2 Review of Treatments

General Overview

Quarantine and phytosanitation treatments can be sorted into several categories: chemical, biological, irradiation and physical. Briefly, chemical approaches include a wide assortment of distinct compounds: (i) fumigants (hydrogen cyanide, phosphine, carbon disulphide, halogenated hydrocarbons such as ethylene dibromide and methyl bromide, and acrylonitrile); (ii) dips (insecticides and soaps); and (iii) controlled or modified atmospheres (often used in combination with a temperature treatment).

Fumigants are the most prevalent, but are losing support because of health, environmental and safety concerns (Stark, 1994; Yokoyama, 1994). The postharvest alternatives to methyl bromide fumigation will be discussed later in this chapter. Controlled atmospheres (CA), reviewed by Carpenter and Potter (1994) and Hallman (1994), involve changing the composition of gases, usually substituting oxygen with nitrogen or carbon dioxide. Insecticides used in dips and sprays include soaps, organophosphorus compounds, organochlorines and insect growth regulators, and these have been reviewed by Hansen and Hara (1994) and Heather (1994). Approval of chemical approaches varies between different jurisdictions.

Biological approaches include the use of natural enemies or microbial agents (generally limited to phytosanitary treatments of stored grains or other durables), host-plant resistance (particularly among cultivars) and pest-free zones, which may be geographical or temporal. For pest-free zones to be effective, the host–pest relationship must be well known, and site manipulation – such as the removal of alternative hosts as well as intensive sampling – may be required. Armstrong (1994a), Greany (1994), Riherd *et al.* (1994), Moore *et al.* (2000) and Schöller and Flinn (2000) have all reviewed different biological methods.

Irradiation, including exposure to gamma and X-rays, is an old technology where dose mortality schedules have been established for several pests on a variety of commodities. Safety, expense, environmental concerns and consumer acceptance interfere with its widespread use. For further information, consult Moy (1985), Burditt (1994) and Nation and Burditt (1994).

Physical methods of quarantine and phytosanitation treatments include mechanical, ultrasound, vacuum and temperature extremes. Mechanical systems use brushes and water sprays (Walker *et al.*, 1996; Whiting *et al.*, 1998; Prusky *et al.*, 1999). Ultrasound produces alternating high and low pressure waves that cause cavitation at the cellular level (Sala *et al.*, 1999) to reduce surface pests on fruit (Hansen, 2001).

Vacuum treatments, applied primarily to durable commodities, are gaining interest due to the development of flexible, low-cost treatment containers (Navarro *et al.*, 2001). Alone, vacuum treatments appear to cause mortality in insects by creating a low-oxygen atmosphere and, in low-moisture environments, may cause rapid dehydration (Navarro and Calderon, 1979). A vacuum microwave (MW) grain dryer was found to rapidly disinfest stored grain of insects (Tilton and Vardell, 1982a, b).

Cold temperature treatments, particularly cold storage, have practical application for many commercial operations (Armstrong, 1994b; Gould, 1994), such as holding commodities before marketing – as well as pest control. Thermal treatments must be precise because of the narrow margin between efficacy and commodity tolerance to the temperature, particularly in fresh fruit and vegetables. Heat treatments have been accepted for commodities entering the USA (USDA, 2005a) and for interstate shipments (see Table 1.2) (USDA,

Table 1.2. Quarantine heat treatments in the USA (from USDA, 2005b, c).

Commodity	Target pests	Treatment schedule
Hot water immersion		
Limes	Mealybugs and other surface pests	49°C or above for 20 min
Longan (lychee from Hawaii)	*Ceratitis capitata, Bactrocera dorsalis*	49°C or above for 20 min
Mango	*Ceratitis capitata, Anastrepha* spp., *Anastrepha ludens*	46°C for 65–110 min, depending on origin, size and shape of fruit
High-temperature forced air		
Citrus from Mexico, infested areas in the USA	*Anastrepha* spp.	Raise centre of fruit to 44°C over 90 min, hold at 44°C for 100 min
Citrus from Hawaii	*Ceratitis capitata, Bactrocera dorsalis, B. cucurbitae*	47.2°C (fruit centre) for at least 4 h total treatment time
Mango from Mexico	*Anastrepha ludens, A. oblique, A. serpentina*	Until seed surface reaches 48°C
Papaya from Chile, Belize and Hawaii	*Ceratitis capitata, Bactrocera dorsalis, B. cucurbitae*	47.2°C (fruit centre) for at least 4 h total treatment time
Rambutan from Hawaii	*Ceratitis capitata, Bactrocera dorsalis*	Raise centre of fruit to 47.2°C over 60 min, hold at 47.2°C for 20 min
Vapour heat treatments		
Bell pepper, aubergine, papaya, pineapple, squash, tomato, courgette from Hawaii	*Ceratitis capitata, Bactrocera dorsalis, B. cucurbitae*	44.4°C (fruit centre) for 8.75 h (heating rate variable)
Clementine, orange, grapefruit, mango from Mexico	*Anastrepha* spp.	Raise centre of fruit to 43.3°C over 8 h, hold at 43.3°C for 6 h
Clementine from Mexico (alternate treatment)	*Anastrepha* spp.	Raise centre of fruit to 43.3°C over 6 h, hold at 43.3°C for 4 h; fruit should be heated rapidly during first 2 h
Lychee from Hawaii	*Ceratitis capitata, Bactrocera dorsalis*	Raise centre of fruit to 47.2°C over 60 min, hold at 47.2°C for 20 min
Mango from Philippines	*Bactrocera* spp.	Raise centre of fruit to 46°C over 4 h, hold at 46°C for 10 min
Mango from Taiwan	*Bactrocera* dorsalis	Raise centre of fruit to 46.5°C, hold at 46.5°C for 30 min
Papaya	*Ceratitis capitata, Bactrocera dorsalis, B. cucurbitae*	Raise centre of fruit to 47.2°C over 4 h
Yellow pitaya from Colombia	*Ceratitis capitata, Anastrepha fraterculus*	Raise centre of fruit to 46°C over 4 h,hold at 46°C for 20 min
Rambutan from Hawaii	*Ceratitis capitata, Bactrocera dorsalis*	Raise centre of fruit to 47.2°C over 60 min, hold at 47.2°C for 20 min

2004). Reviews of heat treatments can be found in Stout and Roth (1983), Armstrong (1994b), Hallman and Armstrong (1994), Sharp (1994a, b) and USDA (2005b). Heat treatments will be discussed in more detail later in this chapter.

Methyl Bromide Fumigation and the Montreal Protocol

For many years, ethylene dibromide was the preferred fumigant against quarantine pests, but was withdrawn in 1984 because of its carcinogenic properties. Since the demise of ethylene dibromide, methyl bromide has become the most popular quarantine treatment (Gaunce *et al.*, 1981; Yokoyama *et al.*, 1990; Moffit *et al.*, 1992). In addition to quarantine uses, methyl bromide has been used extensively for phytosanitary treatments of durables such as dried fruit, nuts, beans, processed foods and pet foods, as well as treatment of processing facilities.

However, methyl bromide was identified by the US Environmental Protection Agency (EPA) under the Federal Clean Air Act (Anon., 1990) and by the Montreal Protocol (Anon., 1995) as having high ozone depletion potential. The EPA mandated the removal of methyl bromide from the chemical register and the phase-out of its production and import into the USA by 31 December 2005.

Similar legislation has occurred in other industrialized countries (see Fig. 1.1). Although methyl bromide fumigation for postharvest quarantine treatments is exempt from the ban, price increases from reduced production, unreliable sources and future restrictions under international agreements (USEPA, 2001) suggest that methyl bromide may become unavailable for quarantine applications as well. Consequently, alternatives to methyl bromide are needed for all postharvest applications.

Practical Alternatives to Methyl Bromide Fumigation

Practical alternatives to methyl bromide must be safe and efficacious, must not reduce product quality, storage life or marketability, must be environmentally acceptable and economically feasible. Some applications require a relatively rapid treatment, either to treat large volumes of product or to meet the needs of specific markets. Although many alternatives have been suggested, most require much longer treatment times, extensive changes to the way processors handle product or substantial capital expenditure.

Alternatives to methyl bromide are easiest to adopt when they serve as drop-in replacements, requiring little change to existing plant infrastructure or

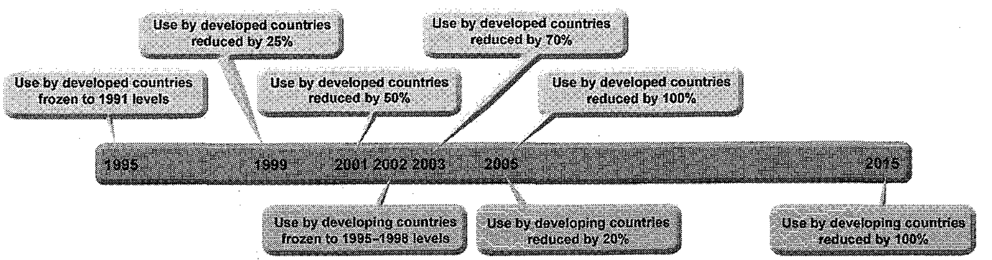

Fig. 1.1. Timeline for the reduction of methyl bromide use globally.

processing procedures. Because other fumigants are considered to be the only such alternatives, they are most likely to be adopted when available. However, issues such as extended treatment times, reduced efficacy and increased costs for some alternative fumigants make them less suitable for certain applications. New fumigants may be developed, but testing and registration of new compounds is a lengthy and expensive process.

Several alternatives have been proposed that do not rely on fumigation for postharvest insect control. These range from single treatments – such as modified atmospheres or vacuum – to combining existing sub-efficacious treatments so that the net efficacy reaches acceptable levels. Related to this is the Systems Approach for quarantine applications, where existing commercial operations, along with treatments that can easily be added without disruption, accumulatively reach the quarantine security level, but not necessarily probit-9. Also, intensive inspection is added to assure compliance.

The industry usually favours this procedure because, with no or few added steps, costs remain low while quality is not adversely affected. This has become the standard for many importing countries, along with a phytosanitation certificate indicating that the commodity has passed the required inspections. Regulatory agencies of both the exporting and importing countries oversee this process. Jang and Moffit (1994) provide a good review of the Systems Approach.

Heat treatments appear as likely candidates for methyl bromide alternatives because: (i) the technology is well established; (ii) they can be applied to a wide range of pests; (iii) there are usually no harmful residues or chemical byproducts; (iv) heat can be generated from a variety of sources; and (v) the costs can usually be controlled. The major impediment is the maintenance of product quality. Dried fruit, nuts and other durables – as well as tropical and subtropical fruit and vegetables – are good candidates for thermal treatments because of their heat tolerances (McDonald and Miller, 1994). However, successful treatments have been developed for temperate fruits as well. Other alternatives to methyl bromide fumigation, in addition to temperature methods, are reviewed by Fields and White (2002) and Vincent *et al.* (2003).

1.3 Survey of Heat Treatments

Early Applications of Heat for Pest Control

Since ancient times, heat in the form of solar energy or fire has been used to control insect pests. Early civilizations killed insect pests in stored grains with the heat of the sun (Cotton, 1963). To control locusts, the Chinese Kingdom of Shang (*c.* 1520–1030 BC) appointed anti-locust officials, who used bonfires to burn collected locusts or repel them (Nevo, 1996). This practice was carried into the 20th century in the USA, when it was suggested for control of chinch bugs (Headlee, 1911) and grasshoppers (Milliken, 1916), a practice that continues to be studied for US rangelands (Vermeire *et al.*, 2004).

In more recent times, the most extensive use of heat treatment has been to control grain insects. For this purpose, heat has been used both as a commodity treatment and as a structural treatment for mills and processing facilities. Thermal treatments against the Angoumois grain moth, *Sitotroga cerealella* (Oliver) (Lepidoptera: Gelechiidae), were used in France for stored grains as early as 1792 (Fields and White, 2002), and later the French used devices known as 'insect mills' for heating infested grain (Dean, 1913).

In the USA as early as 1835, heated rooms were used to control *Sitophilus* spp. (Coleoptera: Curculionidae) in wheat (Oosthuizen, 1935). During the first half of the 20th century, research on heat treatments was conducted on a variety of insects, including (i) the khapra beetle, *Trogoderma granarium* Everts (Coleoptera: Dermestidae) (Husain and Bhasin, 1921); (ii) the red flour beetle, *Tribolium castaneum* (Herbst) F. (Coleoptera: Tenebrionidae) (Grossman, 1931); (iii) the confused flour beetle, *Tribolium confusum* Jacqueline du Val (Coleoptera: Tenebrionidae) (Oosthuizen, 1935); (iv) the Angoumois grain moth (Grossman, 1931; Harukawa, 1941); (v) grain weevils, *Sitophilus* spp. (Back and Cotton, 1924; Grossman, 1931; Tsuchiya, 1943); and (vi) others.

Early work with heat treatments using electromagnetic energy (radio frequency or microwaves) centered primarily on stored-product insects. The lethal thermal effects on insects caused by exposure to radio frequencies were first reported by Lutz (1927) and Headlee and Burdette (1929). Hadjinicolaou (1931) and Whitney (1932) attributed the death of a variety of stored-product pests exposed to high-frequency radio waves to internal heat generated within the body of each insect. Davis (1933) described how radio frequency energy could kill stored-product pests. Mouromtseff (1933) and Ulrey (1936) worked on designing oscillators for use against grain pests. Kuznetzova (1937) showed that the mature larvae of the granary weevil were more resistant to high-frequency electric currents than were other life stages and noted that adults outside the grain were more susceptible than those within.

Heat has been used to disinfest mills and processing plants for some time. Chittenden (1897) recommended using steam on flour mill machinery to control contamination by the Mediterranean flour moth, *Anagast kuehniella* (Zeller) (Lepidoptera: Pyralidae), and recommended 52–60°C for a few hours to kill other grain insects. Dean (1913) noted that the heating of mills in Kansas and other Midwestern states demonstrated the efficacy of this method against all life stages of common mill insects. Pepper and Strand (1935) described how heating the structure of a grain mill to 66°C could control grain pests within 24 h.

Since the late 19th century, heat treatments in the form of hot water dips, vapour heat or hot forced air have been used to treat numerous fresh commodities (Hallman and Armstrong, 1994; Sharp, 1994a). In 1909, one of the earliest attempts at postharvest treatment of a horticultural commodity used immersion of fruit in hot water to control tarsonemid mites (Cohen, 1967).

Vapour heat was first used in Mexico in 1913 to control the Mexican fruit fly, *Anastrepha ludens* (Loew) (Diptera: Tephritidae). Procedures for using vapour heat were also developed to control the Mediterranean fruit fly in Florida citrus (Latta, 1932) and several types of fruits and vegetables in

California (Mackie, 1931). A similar approach was adopted with Texas citrus for fruit fly control (Hawkins, 1932).

Recent Progress in Heat Treatments

Since these early attempts to control insects by thermal methods, the applicable technologies have progressed in mechanical design and theory. Advances in instrumentation now provide accurate measurements of temperature and other treatment variables, and refined techniques have improved precision and replication. The following provides a short review of each of the current thermal methods.

Hot water

Hot (> 40°C) water baths and dips are the simplest form of heat treatment. Because of the aqueous medium, treatments are anaerobic, with a rapid energy transfer. Although the procedure has a long history, hot water treatments for quarantine applications have only recently been approved, primarily for fruit flies in tropical and subtropical fruits (Sharp, 1986; Sharp *et al.*, 1988, 1989a, b, c; Sharp and Picho-Martinez, 1990).

Couey *et al.* (1985) and Couey and Hayes (1986) combined ethylene dibromide fumigation with hot water baths to control tephritid fruit flies in Hawaiian papayas. Morgan and Crocker (1986) recommended 49°C water baths for 15 min to control weevils in acorns. For other pests, McLaren *et al.* (1997, 1999) described a commercial-scale 2-min hot water bath (50°C) to control the New Zealand flower thrips, *Thrips obscuratus* (Crawford) (Thysanoptera: Thripidae), on apricots, peaches and nectarines. Other examples of the use of hot water for commercial treatments are found in Chapter 13, this volume, and a discussion of thermal death studies using hot water baths in the laboratory is in Chapter 5, this volume.

Vapour

Like water baths, vapour heat treatments use moisture (as saturated air) to transfer thermal energy, usually involving air movement. As presented earlier in this chapter, vapour heat treatment is an old process. It was developed by Baker (1952) for citrus and is now widely used for papaya, pineapple, bell pepper, eggplant, tomato and zucchini (USDA, 2005c). Sinclair and Lindgren (1955) modified vapour heat treatments for California citrus and avocados, and Seo *et al.* (1974) applied this technology for treatment against the oriental fruit fly, *Bactrocera dorsalis* (Hendel) (Diptera: Tephritidae). In Florida, McCoy *et al.* (1994) presented a vapour heat treatment against the eggs of the Fuller rose beetle, *Asynonychus godmani* (Crotch) (Coleoptera: Curculionidae). For more information on vapour heat treatments, see Hallman and Armstrong (1994) and Chapter 13 of this volume.

Forced hot air

Forced hot air treatment is similar to vapour heat treatment, but does not have the moisture component and is a more recent development (Armstrong *et al.*, 1989). Improvements in temperature and moisture monitoring and air delivery have advanced forced hot air treatments (Hallman and Armstrong, 1994). Forced hot air treatments are being devised for commodities normally subjected to vapour heat treatment and have also been applied to new commodities. Their disadvantages are the long treatment durations and sophisticated equipment needed for operation. Also, not all horticultural commodities are suitable, such as avocado (Kerbel *et al.*, 1987).

Heat treatments for durable commodities

Heat has been effective against stored-product pests of durable products such as grains, nuts, dried fruits, wood products and museum artefacts. Most recent work has been carried out on grain pests, and there exists a considerable body of laboratory work on the thermal sensitivity of those (Fields, 1992; Saxena *et al.*, 1992; Mahroof *et al.*, 2003, 2005; Boina and Subramanyam, 2004). Dry heat (82.2°C for 7 min) has been recommended for disinfection of milled products of the khapra beetle, *Trogoderma granarium* Everts (Coleoptera: Dermestidae) – an important quarantine grain pest (Stout and Roth, 1983).

In order to improve the efficiency and reduce the cost, continuous flow, fluidized-bed heating systems for grain have been examined in Australia (Dermott and Evans, 1978; Evans *et al.*, 1983). Commercial heat treatments (usually at 56°C) to control insects in imported wood packaging have been approved in Japan, China, New Zealand, Australia, Europe, North America and most of South America (Anon., 2005). More information on heat treatments for grain may be found in Chapter 8, this volume.

Heat treatment for structures

The application of dry heat to structures to eliminate pests is an attractive alternative to fumigation, and has been used successfully for decades. Sheppard (1984), Heaps (1988, 1996) and Heaps and Black (1994) recount the measures used in commercial mills and food plants when using heat to control stored-grain pests residing in the infrastructures. More recent work has better defined the treatment parameters (Mahroof *et al.*, 2003; Akdoğan *et al.*, 2005). Detailed information on structural heat treatments for control of storage insects can be found in Chapter 8, this volume.

In addition to stored-product pests, structural heat treatments have been applied to a variety of other structural pests, including roaches (Forbes and Ebeling, 1987), termites (Forbes and Ebeling, 1987; Lewis and Haverty, 1996; Zeichner *et al.*, 1998), ants (Forbes and Ebeling, 1987), and powderpost beetles (Ebeling *et al.*, 1989). Ebeling (1994) reviewed the thermal parameters and equipment needed to control structural pests. Quarles (1994) noted that thermal treatments were as effective as conventional fumigations for structural pest control and that their costs were decreasing.

High-temperature controlled atmospheres

Another anaerobic procedure combines forced hot air with an oxygen-poor environment, achieved by replacing oxygen with nitrogen or using high concentrations of carbon dioxide. The mechanism of control is to increase respiratory demands for the target pest – as during heating – yet restrict the amount of oxygen available, leading to metabolic arrest and death. Besides exchanging gases, sophisticated instrumentation may be used like those in the forced hot air system.

The greatest advancement and application of high-temperature controlled atmosphere (HTCA) treatments has been against stored-product pests. Many studies on controlled atmosphere (CA) targeting stored-product pests have noted the relationship between temperature and mortality (Harein and Press, 1968; AliNiazee, 1972; Storey, 1975, 1977; Banks and Annis, 1977; Bailey and Banks, 1980; Soderstrom *et al.*, 1986; Delate *et al.*, 1990; Wang *et al.*, 2001). High-temperature controlled atmosphere treatments have now replaced methyl bromide fumigation, particularly in Europe, for pest control of stored food items, spices, grain in silos and ships, furniture and floorboards (Bergwerff and Vroom, 2003).

Studies on HTCA treatments for horticultural crops are of more recent origin. Early experimental units were based on forced hot air design (Gaffney and Armstrong, 1990; Gaffney *et al.*, 1990; Sharp *et al.*, 1991; Neven and Mitcham, 1996). Many HTCA studies for horticultural pests were for control of the light brown apple moth, *Epiphyas postvittana* (Walker) (Lepidoptera: Tortricidae), and other pests of New Zealand apples (Whiting *et al.*, 1991, 1995, 1999a, b; Dentener *et al.*, 1992; Lay-Yee *et al.*, 1997; Chervin *et al.*, 1998; Whiting and Hoy, 1998).

Neven and Mitcham (1996) discussed the development of an HTCA treatment known as the Controlled Atmosphere Temperature Treatment System (CATTS). Applications that show promise include codling moth on fresh sweet cherries (Shellie *et al.*, 2001; Neven, 2005) and nectarines and peaches (Obenland *et al.*, 2005). Neven (2004) provided further discussion of CATTS and other HTCA treatments for fresh commodities. More information on heat with controlled atmospheres may be found in Chapter 10, this volume.

Solar energy

Very little has been done using solar energy to control insects. Although the approach is simple and has potential for long-term storage in rural areas and developing countries, there are problems with temperature control in terms of the regulation of consistent temperatures. Most work with solar heat treatments of commodities has targeted bruchid pests of seeds using a variety of solar heating methods including plastic bags, corrugated metal and wooden racks (Murdock and Shade, 1991; Kitch *et al.*, 1992; Chinwada and Giga, 1996; Ntoukam *et al.*, 1997; Arogba *et al.*, 1998; Songa and Rono, 1998; Ugwu *et al.*, 1999; Chauhan and Ghaffar, 2002).

Solar heating has been used to control other stored product and fruit pests, including: (i) the hide beetle in dried mullet; (ii) the Indianmeal moth in peaches; (iii) the merchant grain beetle in oatmeal (Nakayama *et al.*, 1983); (iv) the larger grain borer in maize cobs (McFarlane, 1989); and (v) nitidulid beetles in figs (Shorey *et al.*, 1989). Solar heating has also been suggested for museum artefacts (Baskin, 2001; Brokerhof, 2003; Pearce, 2003).

Infrared

Infrared is strongly emitted by hot substances and readily absorbed by living tissue, making it a logical choice for thermal treatment. Considerable research has been carried out using infrared heat to control internal pests of grains (rice weevils, lesser grain borers and Angoumois grain moths) using short exposures to temperatures of 56–68°C (Schroeder and Tilton, 1961; Tilton and Schroeder, 1963; Kirkpatrick *et al.*, 1972).

Kirkpatrick and Tilton (1972) measured mortalities of 12 species of stored product beetles in soft winter wheat and obtained > 99.5% mortality for all when treated at 65°C for less than 1 min. Kirkpatrick (1975) treated wheat infested with rice weevils and lesser grain borers in bulk with infrared and obtained > 93% mortality after 24 h exposure to 43.3°C. More recently, Subramanyam (2004) reported mortality from flameless catalytic infrared heaters on adults of the sawtoothed grain beetle, rice weevil and red flour beetle.

Microwave

The microwave (MW) region of the electromagnetic spectrum is from 1 to 100 GHz, between infrared and FM radio, and it is close to radio frequency range (see Fig. 1.2). Microwaves have been applied to a wide range of products, from soil and museum artefacts to fresh fruits. However, the most predominant efforts with current MW technology are in the control of pests of grain and stored products (Nelson 1973, 1996; Roseberg and Bögl, 1987; Nelson *et al.*, 1998; Wang and Tang, 2001).

A number of studies developing MW grain drying systems noted that insect disinfestation was an additional benefit (Hamid and Boulanger, 1970; Boulanger *et al.*, 1971; Tilton and Vardell, 1982a, b). Langlinais (1989)

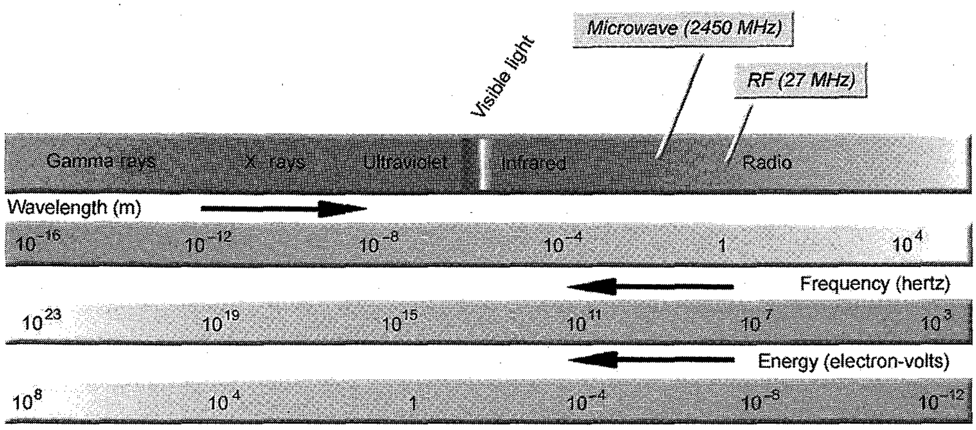

Fig. 1.2. The electromagnetic spectrum.

demonstrated that the confused flour beetle and flat grain beetle, *Cryptolestes pusillus* (Schnherr) (Coleoptera: Cucujidae), can be economically controlled by MW exposures. Other applications for MW in durable food commodities include treatment for pecan weevil in pecans (Nelson and Payne, 1982), red flour beetle, sawtoothed grain beetle, almond moth and Indianmeal moth in walnuts (Wilkin and Nelson, 1987) and almond moth in sun-dried figs (Baysal *et al.*, 1998).

Investigations into the MW applications of fresh horticultural commodities have been limited. In tests to control the mango weevil, *Cryptorhynchus mangiferae* (F.) (Coleoptera: Curculionidae), Seo *et al.* (1970) observed that MW exposures of 45 s resulted in cooked rind and pulp of treated mangoes. Sharp (1994b) described the equipment used to study the effects of MW on grapefruits infested with the Caribbean fruit fly, *Anastrepha suspense* (Loew) (Diptera: Tephritidae). Sharp *et al.* (1999) examined the effect of MW on mature larvae of the Caribbean fruit fly and concluded that rapid heating imposes serious constraints on the use of heat-induced mortality. Ikediala *et al.* (1999) improved treatment efficacy against the third-instar codling moth by adding 1–2 day cold storage after MW treatments.

MW energy has been explored in the treatment of wood and wood products (Hightower *et al.*, 1974; Burdette *et al.*, 1975; Mashek, 1998) and other non-food items (Reagan *et al.*, 1980; Hall, 1981). Lewis and Haverty (1996) compared MW treatments to five other methods of controlling the drywood termite and obtained 99% mortality 4 weeks after treatment.

To control the Asian longhorned beetle, *Anoplophora glabripennis* (Motschulsky) (Coleoptera: Cerambycidae), Fleming *et al.* (2003) found that MWs heated wood to the controlling temperature of 60°C within 5 min compared to 123 min with conventional heating, and recommended MW treatment to eradicate Asian longhorned beetles in solid wood-packing materials. Philbrick (1984) was concerned about seed viability and slight morphological changes in specimens when MWs were used for herbarium pest control. As with the other applications, MWs work best on dried subjects.

Radio frequency

Radio frequency (RF) waves are at the lower frequency range of the electromagnetic spectrum, with longer wavelength, and the most commonly accepted frequencies used for industrial purposes are 13.56 MHz, 27.12 MHz and 40.68 MHz (Tang *et al.*, 2000). RF energy generates internal heat by resistance from a very rapid change in molecular polarity and migration of charged ions.

The advantages of RF heating are: (i) it is very fast; (ii) it can penetrate deep into the target material because of its long wavelength; (iii) it can produce differential heating between the product and the pest; and (iv) it leaves no toxic residues.

Other than investigations with grain insects (Nelson and Kantack, 1966; Nelson, 1996) and recent progress described later in this volume, RF has not maintained the attention it received in the middle of the last century. Early reviews are provided by Ark and Parry (1940), Webber *et al.* (1946), Frings (1952) and Thomas (1952). Later commentaries are given by Whitney *et al.* (1961) and Watters (1962).

Recent pest control efforts using RF have targeted fresh fruits and nuts (Ikediala *et al.*, 2000; Mitcham *et al.*, 2004; Wang *et al.*, 2005b). Wang *et al.* (2005a) demonstrated the commercial feasibility of RF methodologies to control stored-product pests of walnuts at a walnut-packing house. In Chapters 12 and 13 respectively, this volume, the properties of electromagnetic energy treatments and their potential as commercial treatments will be discussed more thoroughly. A comparison of the heat treatment strategies described above is given in Table 1.3.

Table 1.3. Comparison of heat treatment strategies.

Strategy	First used	Commodity	Advantages	Disadvantages
Hot water	1925	Fruits, bulbs, ornamentals, seeds	Simplest, efficient	Surface heating first; fuel costs
Vapour heat	1913	Fruits, vegetables	Relatively simple	Expensive facilities; surface heating first; slow
Forced hot air	1989	Fruits, vegetables	Product quality retained	Expensive facilities; surface heating first; slow
Dry heat	1792	Structures, grains, fibres, museum artefacts, books	Simple; versatile, known technology	Surface heating first; slow
CATTS	1996	Experimental	Faster than other air methods	Surface heating first; complicated, expensive facilities
Solar	1983	Experimental, structures	Simple, inexpensive	Variable effects
Electromagnetic energy	1927	Experimental, grains, seeds, nuts	Very fast; internal heating first	Expensive facilities; variable effects

1.4 Heat Treatments for Microbial Control

Heat treatments also affect microbial populations on commodities and the incidence of natural decay. Heat treatments are applied to some commodities specifically for decay control, while in other cases the heat treatment is applied for the purpose of insect control and has a secondary effect on decay susceptibility. The secondary effect on decay could be beneficial, resulting in a lower incidence of decay, or detrimental, increasing decay susceptibility. The tolerance of the commodity to the heat treatment has the greatest influence on resultant decay susceptibility. In Chapter 7, this volume, the use of heat treatments for microbial control will be discussed.

1.5 Tolerance of Commodities to Heat Treatments

The tolerance of commodities to heat for insect or decay control must be carefully considered in development of such treatments. If the commodity quality is compromised significantly, the treatment will be unsuccessful. Commodity tolerance to the various methods of heating (water, air, RF, etc.) varies. In some cases, product quality and postharvest life is improved by heat treatment: ripening can be delayed, extending storage life; decay incidence may be reduced.

However, most heat treatments, particularly those designed for control of internal insect pests, cause some detrimental effects on product quality. There are some strategies for increasing the tolerance of commodities. The overall goal is to minimize detrimental effects while maintaining treatment efficacy. See Chapter 4, this volume, for detailed information about the tolerance of commodities to heat treatment and Chapter 11, this volume, for a discussion of induced heat tolerance.

1.6 Conclusions

Insects affect the storage, marketing and trade of food products, resulting in considerable economic loss. Methods to prevent or control insect infestations are needed to maintain food quality and allow free movement of produce. Although chemical fumigation is still the most commonly used control method, environmental and safety issues concerning fumigants provide a strong incentive for the development of alternative, non-chemical methods.

The wide variety of heat treatments currently available or in development show great potential as alternatives, but much work is needed to understand better the biological and physical processes involved. This book provides the foundation for advancing the application of postharvest heat treatments for effective pest control.

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